Higher School of Communication of Tunis

Scope statement: Soil Monitoring and Management System

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1 Concept

1.1 Project context

The project operates within the domain of precision agriculture, addressing the global challenge of feeding a growing population while promoting sustainability. Traditional farming practices, particularly those related to soil nutrient analysis and crop selection, are often labor-intensive, time-consuming, and prone to subjective errors. This leads to the inefficient use of critical resources (fertilizers and water), resulting in suboptimal yields and increased environmental impact.
The recent advancements in the Internet of Things (IoT), Machine Learning (ML) and and Location-Based Services (LBS) offer a powerful solution to overcome these limitations. This project leverages these technologies to create an integrated system that provides farmers with real-time, accurate data and informed decision-making tools, thereby facilitating the shift toward more efficient, data-driven, and sustainable agricultural management.

1.2 Problem statement

Farmers currently lack an integrated, real-time system for monitoring soil conditions and receiving customized, data-driven recommendations. Specifically, the problem is threefold:

1. **Lack of Real-Time Soil Intelligence:**Farmers cannot continuously and accurately monitor critical soil parameters, such as NPK nutrient levels, moisture, temperature, and humidity, leading to delayed or guesswork-based interventions.

2. **Suboptimal Resource Management:** The reliance on traditional methods results in inefficient application of fertilizers and incorrect crop choices, leading to reduced crop productivity and unnecessary resource wastage.

3. **Absence of Supply Chain Transparency:**There is no easy mechanism to track the treatments and fertilizers applied during production, preventing consumers from assessing the quality and safety of the produce they purchase.

1.3 Objectives

The project's overarching goal is to design, implement, and validate an ML-enabled IoT system that transforms agricultural decision-making from subjective guesswork into a data-driven process.

Core Technical Objectives

- **Integrate IoT Sensor Network:** To successfully integrate IoT sensors capable of continuously collecting and transmitting real-time data on soil NPK levels, moisture, temperature, and humidity using the MQTT protocol.

- **Implement ML-Driven Recommendations:** To employ Machine Learning algorithms (CatBoost, Random Forest) to accurately analyze the collected sensor data and generate customized recommendations for high-yielding crops and precise fertilizer types and quantities.

- **Establish a Reliable Middleware:** To establish a robust and reliable middleware layer to efficiently handle the ingestion of high-volume IoT sensor data, process ML predictions, and manage seamless user interactions.
- **Develop User Interface (PWA):**To implement a Progressive Web Application (PWA) for real-time data visualization, remote system management, and delivery of customized recommendations and alerts to the end-users.
- **Geographical Contextualization (LBS):** To integrate a Location-Based Service to associate all sensor data and ML predictions with precise geographical coordinates.

Strategic and Impact Objectives

- **Enhance Resource Efficiency:** To enable farmers to optimize resource utilization (water, fertilizer) and significantly boost crop productivity by providing actionable, data-backed insights.
- **Ensure Quality and Transparency:** To create a data structure and system feature that tracks all field treatments and fertilizers applied, allowing for the assessment of crop quality and safety at the consumer level.
- **Validate System Performance:** To conduct rigorous field testing and comparative analysis to scientifically validate the system's effectiveness and its superiority over traditional agricultural methods.

2 Client

The primary clients of the Soil Monitoring System are farmers and agricultural cooperatives aiming to optimize irrigation and fertilizer usage through simple yet effective monitoring tools. Current farming practices often rely on manual observation and estimation, which may lead to over-irrigation, under-irrigation, or inefficient fertilizer application. These issues result in wasted resources, reduced crop quality, and lower productivity.

The clients expect the system to address the following needs:

- **Temperature monitoring:** Continuous measurement of air temperature to ensure crops grow within suitable environmental conditions.
- **Humidity monitoring:** Accurate tracking of humidity levels to help determine irrigation requirements and avoid plant stress.
- **Fertilizer optimization:** Providing recommendations for efficient fertilizer usage based on collected data, reducing costs and improving crop yield.
- **Accessibility:** A cloud-based web application accessible through smartphones or computers, offering real-time data visualization and alerts.

The expected benefits for the client are:

- **Improved productivity:** Healthier crops and higher yields due to precise monitoring of environmental conditions.
- **Resource efficiency:** Reduced water and fertilizer consumption, ensuring that inputs are applied only when necessary.
- **Sustainability:** Adoption of eco-friendly practices that protect soil quality and minimize environmental impact.
- **Ease of use:** A simple and user-friendly solution suitable even for clients with limited technological knowledge.

Target Population

The Soil Monitoring System is designed for:

- **Small and medium-scale farmers** who need cost-effective tools to optimize irrigation and fertilizer use.
- **Large-scale farms and cooperatives** seeking centralized monitoring to manage multiple fields efficiently.
- **Agricultural researchers and institutions** analyzing the impact of temperature, humidity, and fertilizer management on crop growth.
- **Organizations and associations** promoting sustainable agriculture and efficient resource management.

3 Functional need

3.1 Sensors and IoT network

The IoT network will utilize a set of sensors to continuously monitor the environmental and soil conditions of the crops. The main sensors include:

- Temperature Sensor: Measures the ambient temperature around the plants to ensure that it remains within the optimal range for crop growth.
- Humidity Sensor: Monitors the environmental humidity, which directly impacts plant health and disease susceptibility.
- NPK Sensor: Measures the Nitrogen (N), Phosphorus (P), and Potassium (K) levels in the soil, providing insight into soil fertility and nutrient availability.

The collected data will be transmitted from the sensors to a Raspberry Pi board, which will act as the IoT gateway. The gateway will forward the data to the Cloud using an MQTT broker for processing and storage. An alert system will notify the user in case of abnormal values (e.g., nutrient deficiencies, excessive temperature), and notifications can be configured or disabled by the user.

3.2 PWA application

The Progressive Web Application (PWA) will enable users to:

- Visualize sensor data (temperature, humidity, and NPK values) in real time and over selected time periods through interactive graphs and tables.
- Receive AI-based recommendations for crop management, including optimal fertilizer usage and crop- specific advice derived from the monitored parameters.
- Notify the user of abnormal soil parameters values.

4 Machine learning integration

Crop Recommendation - CatBoost

The crop recommendation system utilizes the **CatBoost** algorithm, specifically chosen for its expertise in handling complex agricultural data. This gradient boosting technology achieves a remarkable accuracy of **97,5%**. Its advanced architecture ensures highly reliable predictions.
The analysis processes seven crucial agronomic and environmental parameters. The model integrates real-time soil NPK levels and current climatic conditions. Soil moisture and precipitation data complete the analytical profile.

Fertilizer Recommendation - Random Forest

For fertilizer prescription, the system employs **Random Forest** optimized with **GridSearchCV**. This combined approach achieves exceptional accuracy of **99,56%**. Automatic hyperparameter optimization ensures maximum performance.
Model fine-tuning is accomplished through systematic optimization. **Cross-validation** enhances the robustness of the provided recommendations. The obtained results significantly outperform existing conventional methods.

5 Equipment

After conducting research, we have identified the following elements as necessary:

- DHT22 : Temperature and humidity sensor for monitoring environmental conditions.
- NPK Sensor: For measuring Nitrogen, Phosphorus, and Potassium levels in the soil to assess soil fertility.
- Raspberry Pi 4: Serves as the IoT gateway to collect sensor data and transmit it to the Cloud via an MQTT broker.
- MicroSD card (minimum 16 GB): For installing the Raspberry Pi operating system and software.
- Jumper wires: For connecting sensors to the Raspberry Pi.

6 Technologies choice

6.1 Back-end

- MongoDB: A NoSQL document-oriented database used for storing user data. It is practical and easy to use in conjunction with Jakarta EE.
- HiveMQ: HiveMQ is a widely used MQTT broker, serving as an intermediary for efficient and reliable messaging between IoT devices and the middleware and is available on the cloud.

6.2 Middleware

- JAX-RS: Java API for RESTful Web Services is a Java programming interface for creating web services with a REST architecture.
- Jakarta Websocket: Provides a standard API for creating WebSocket-based communication between server and client. In this project, it will be used to push real-time sensor updates and alerts from the middleware to the PWA application.
- WildFly: WildFly, formerly known as JBoss Application Server or JBoss, is a free and open-source Java EE application server written in Java and released under the GNU LGPL license. It can be used on any operating system that provides a Java virtual machine.

6.3 Front-End

- PWA (Progressive Web App): A PWA is a cross-platform web application that provides a native-like experience to users. It allows you to develop applications for multiple platforms using web technologies like HTML, CSS, and JavaScript. PWAs are easy and quick to code and do not require prior web development knowledge.

6.4 IoT integration

- Node-RED: Node-RED is an open-source, flow-based development tool for visual programming, widely used in IoT scenarios. It allows for easy integration of sensors, gateways, and cloud services through a drag-and-drop interface. In this project, Node-RED will run on the Raspberry Pi to collect sensor data (temperature, humidity, and NPK), preprocess it if needed, and publish it to the MQTT broker for further processing by the middleware.

7 Architecture

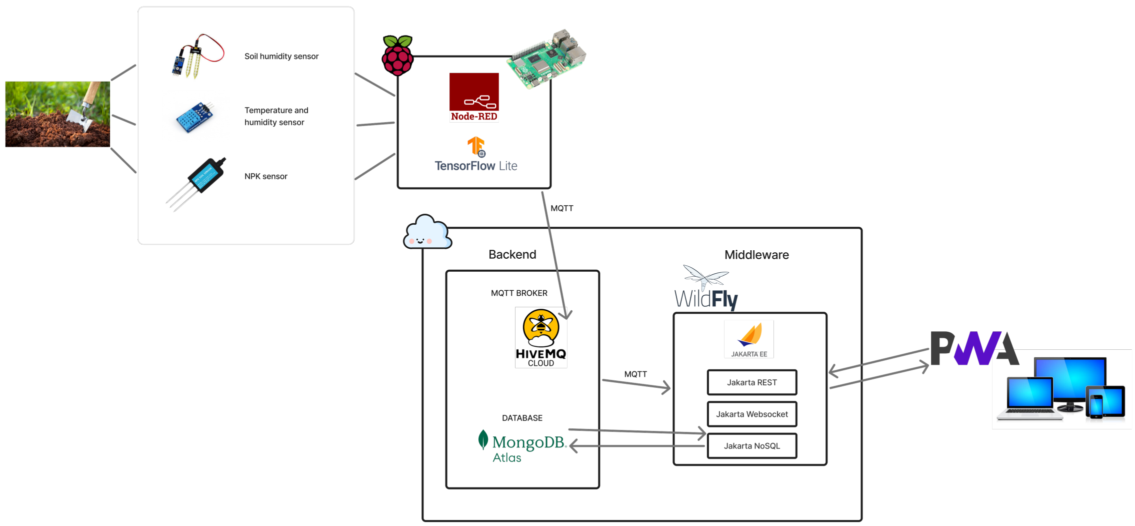

Figure 1: Architecture

The diagram above describes the main architecture of the plant monitoring system which is mainly composed by Backend, Middleware and Frontend.

8 Timeline and tasks

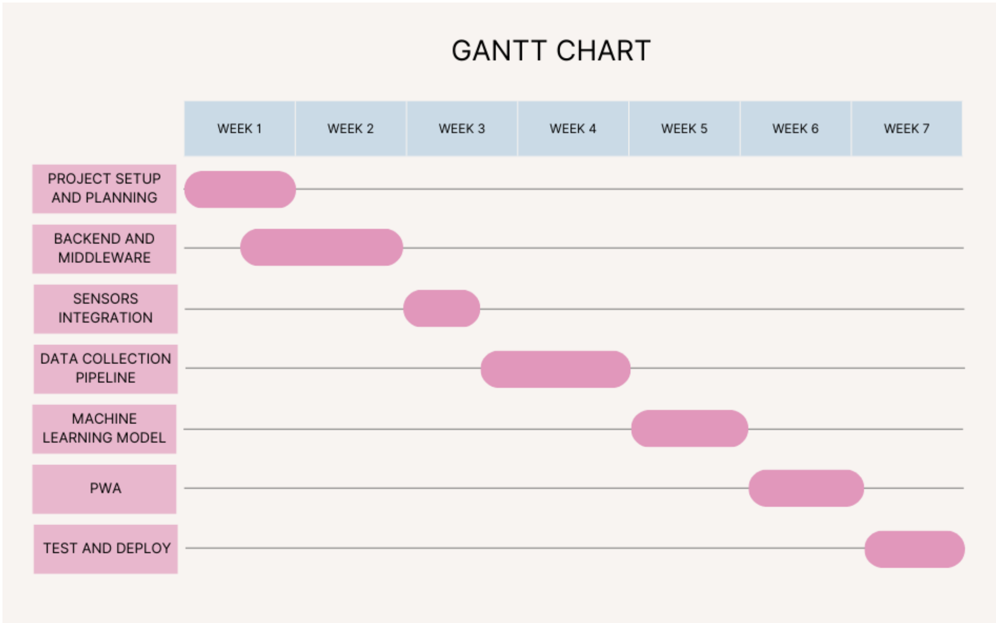

Figure 2: Gantt Diagram.

The Gantt chart in figure 2 illustrates the project timeline, showing the main tasks and their duration throughout the seven-week period from October 27 to December 11. It highlights key tasks and ensures that each phase from setup and sensor integration to middleware development, machine learning, PWA, and final deployment is completed within the planned timeframe.

9 Methodology

Throughout the project, we will use Extreme Programming (XP), a disciplined Agile methodology that emphasizes high-quality software delivery through frequent feedback, close collaboration, and rapid adaptation. XP's iterative nature is exceptionally well-suited for our project, where the short timeline and potential for requirement changes demand a flexible and responsive approach.

9.1 Core Values

Extreme Programming is founded on five core values:

- **Communication**: Continuous information exchange among team members ensures a shared understanding of system requirements and goals.
- **Simplicity**: We focus on designing the simplest possible solution to reduce complexity and improve code maintainability.

- **Feedback**: Rapid feedback loops from continuous testing enable early identification and resolution of issues throughout the development cycle.
- **Courage**: Team members are empowered to speak openly about challenges, refactor code when necessary, and adapt to changing requirements.
- **Respect**: Every team member's perspective is valued, promoting a supportive and collaborative work environment.

9.2 Development Process

The XP methodology structures development into iterative cycles illustrated in figure 3 with five key phases:

1. Planning: In the initial stage, we create our own user stories and define the desired outcomes. The team estimates effort for each story and prioritizes them to create a release plan.
2. Design: Guided by the value of simplicity, the team creates minimal design for current user stories. Shared metaphors or analogies help maintain a clear, logical system structure that avoids unnecessary complexity.
3. Coding: This phase involves the actual implementation of user stories. As a team of four, we will implement features using pair programming (two developers working together at one workstation). This approach enhances code quality through real-time review and facilitates knowledge sharing.
4. Testing: Testing is a cornerstone of XP.It primarily involves two key levels: unit tests and acceptance tests.Unit tests, which are automated, check if specific features work correctly. Acceptance tests, conducted by customers, ensure that the overall system meets initial requirements. This continuous testing ensures the software's quality and alignment with customer needs.
5. Listening: Listening emphasizes continuous communication and feedback. Coaches and project managers play a pivotal role in conveying the business logic and expected value to the team, ensuring a shared understanding of the project's goals and requirements.

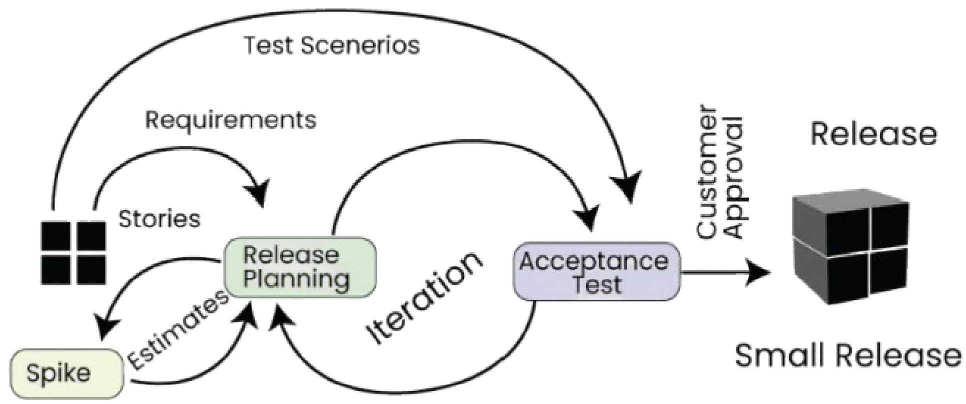

Figure 3: Extreme Programming Life Cycle

10 Limitations

While the Soil Monitoring and Management System offers significant advantages for precision agriculture, certain limitations must be considered:

- **Internet Dependency:** The system requires stable internet connectivity to send sensor data to the cloud and provide real-time visualization. In rural areas with weak or unstable connections, some features may be delayed or unavailable.
- **Sensor Accuracy and Calibration:** Temperature and humidity sensors may be affected by environmental factors such as dust, wind, or direct sunlight. Regular calibration and maintenance are necessary to ensure reliable measurements.
- **Limited Scope of Parameters:** The system monitors only temperature, humidity, and fertilizer optimization. Other critical factors such as soil pH, rainfall, or pest presence are not included in this version, which may limit decision-making accuracy.
- **Energy Consumption:** Continuous monitoring requires stable power supply for the Raspberry Pi and sensors. In the absence of power or battery backup, the system may experience downtime.
- **Fertilizer Optimization Assumptions:** Recommendations for fertilizer usage rely on predefined models and thresholds. They may not always perfectly adapt to different soil types, crop varieties, or environmental conditions without further customization.
- **Cost of Deployment:** Although relatively low-cost, initial investment in Raspberry Pi, sensors, and cloud services may remain a barrier for small-scale farmers with limited resources.

- **Environmental Variability:** Local microclimates, unexpected weather changes, or irrigation system malfunctions may cause discrepancies between sensor readings and actual crop conditions.

11 Business study

The Business Study section provides an overall view of our project's business model and marketing policy.

11.1 Business Model Canvas (BMC)

The Business Model Canvas serves as a visual representation of our project's main aspects, such as value proposition, customer segmentation, channels, cost structure, revenue stream, and more. The BMC is depicted in the figure below:

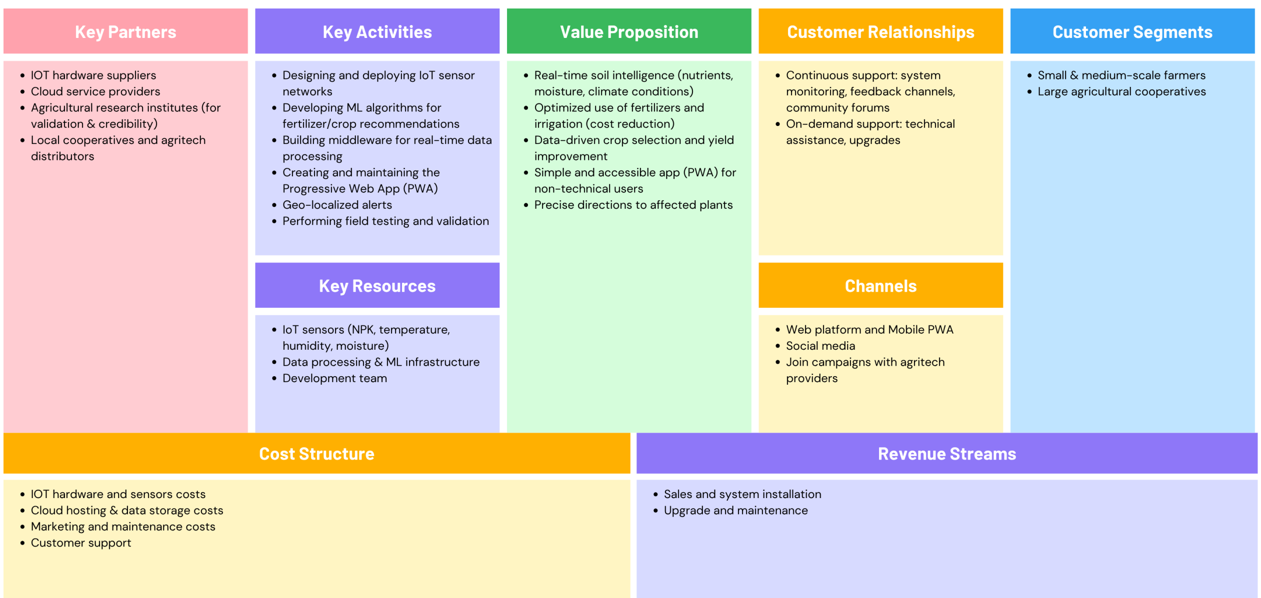

Figure 4: Business Model Canvas

11.2 SWOT Analysis

To better understand the strategic position of the Soil Monitoring System, a SWOT analysis is conducted. It evaluates the system's internal strengths and weaknesses as well as external opportunities and threats, providing insights into its potential for adoption, growth, and long-term success in precision agriculture.

Figure 5: SWOT Analysis

12 Deliverables

- Source code of the various project components on GitHub
- Prototype of the intelligent soil monitoring system.